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STAGE PREDICTIONS FOR FLOOD CONTROL OPERATIONS

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PAPERS

STAGE PREDICTIONS FOR FLOOD CONTROL OPERATIONS

By Ralph E. King[1]

Synopsis

The problems relative to the prediction of stages in the lower Mississippi River Valley during flood periods are the subject of this paper. The development of various forecasting techniques and the advantages and limitations of these techniques with respect to use on the Mississippi River are briefly outlined. Methods used by the Stage Prediction Section of the Mississippi River Commission are explained, with emphasis being given to the method used for reaches which are influenced by inflows from major tributaries. Conclusions as to the type of forecasting procedure necessary to obtain reliable stage predictions on the lower Mississippi River are presented.

Introduction

Principles of Stage Forecasting.—The coming of spring brings a promise of relief to the people who inhabit the colder portions of this country, but to the residents of the lower Mississippi River Valley spring brings a threat of disaster. From the confluence of the Mississippi River and the Ohio River at Cairo, Ill., a thousand miles southward to the Gulf of Mexico the adequacy of the levee system to confine the upward surging floodwaters is of universal concern. To the engineers responsible for the safety of the valley an accurate forecast of the crest stages that will be reached is of vital importance. Stage forecasters, armed with the records of past floods and a sublime faith in the future, suddenly become either important citizens or public enemies, depending on the accuracy of their predictions.

The forecasting of flood stages has been separated into the following classes by Merrill Bernard,[2] M. ASCE:

Note.—Written comments are invited for publication; the last discussion should be submitted by January, 1952.

[1] Engr., Mississippi River Commission, Vicksburg, Miss.

[2] "Recent Developments in Flood-Forecasting," by Merrill Bernard, *Transactions*, American Geophysical Union, Vol. 20, 1939, p. 187, Table 1.

a. Prediction of the maximum flood for the purpose of establishing the capacity limits of control works.

b. Prediction of the probable flood for the purpose of evaluating the accepted tolerances in the design of control works.

c. Prediction of the individual flood for the purpose of preventing loss of life and reducing damage to a minimum.

The forecast for the maximum flood is expressed in terms of magnitude and duration; the forecast for the probable flood in terms of magnitude, duration, and frequency; and the forecast for the individual flood in terms of magnitude, duration, and expected time of occurrence. This paper deals only with the individual-flood type of forecast.

During the flood season almost every operation of the Corps of Engineers, United States Army, throughout the Mississippi River alluvial valley is for the purpose of controlling or minimizing the destructive forces of the floodwaters. Levees must be patrolled constantly. Forces must be mobilized for immediate action, and materials and equipment for emergency operations must be available at the time and place needed. Headwater reservoirs must be operated so as to secure the greatest reduction in the crest of the main stream, and at the same time the operation of floodways and the flooding of leveed backwater areas must be carefully planned. Areas which will be inundated by such operations must be evacuated to prevent loss of life, and levees must be raised or strengthened in critical reaches. Detailed observations of stage and discharge of the current flood must be made so that information will be available for future study. All of these operations are based primarily on stage forecasts.

Factors Affecting the Forecast.—Stage forecasts used in planning and executing flood-fighting activities must possess a degree of accuracy sufficient to insure the completion of all essential operations and the avoidance of useless operations. The mere undertaking of a flood-fighting operation is of very little value, since the successful completion prior to the occurrence of the crest stage is the only criterion by which the operation can be judged. Consequently, a crest forecast must not only be sufficiently accurate as to the stage expected but also must be made far enough in advance of the crest so that time will be available for mobilization and the successful completion of the operation. Needless to say, the accuracy of any forecast decreases as the number of days for which the forecast is made increases.

Stages in any reach of a river are affected by the flow received from the adjacent upstream reach and by the volume of water introduced into the reach by tributaries and rainfall or lost through outlet channels. On the lower Mississippi River the effect of channel storage (including wedge storage) is very pronounced, and studies of past floods on the lower Mississippi River show that the effect of storage varies considerably for different floods. These studies indicate that the amount of water going into storage is a function of both the stage height and the rate of change in stage. The operation of floodways is based on stage forecasts which must then be revised to reflect the effect of such operation. Planned variations in flow releases from flood control reservoirs must be taken into account by the stage forecaster. Since the operations of flood control reservoirs for the purpose of decreasing crests

on the main river must be properly timed with the hydrograph of the main river, these operations must be based on stage forecasts for the main river. This mutual dependence forces the reservoir operator and the stage predictor to work hand in hand.

Other factors that may seriously impair the usefulness of stage forecasts are the accuracy of the observed stages and discharges used as a basis for forecasting and changes that occur in the regimen of the river. If stage predictions are to be successfully used for the planning and execution of emergency operations during flood periods, all of these influencing factors must be considered and their effects evaluated within reasonable limits of accuracy.

Development of Stage Relation Curves

The earliest forecasting methods were probably simple "rules of thumb" similar to the one that estimated the crest stage at Vicksburg, Miss., to be 2 ft below the Cairo crest on the first rise of the flood season and the same as the Cairo crest on subsequent rises. Another similar rule states that the crest stage at Cairo would not exceed 50 ft unless the Ohio River stage at Cincinnati, Ohio, exceeded 50 ft. The limitations of the first rule are readily apparent since it can only apply to average conditions. The second rule was definitely disproved in 1943 when a crest stage of 36.0 ft at Cincinnati combined with one of the larger upper Mississippi River floods to produce a stage of 53.0 ft at Cairo. The floods of 1944 and 1945 also produced crests that demonstrated the fallacy of the second statement.

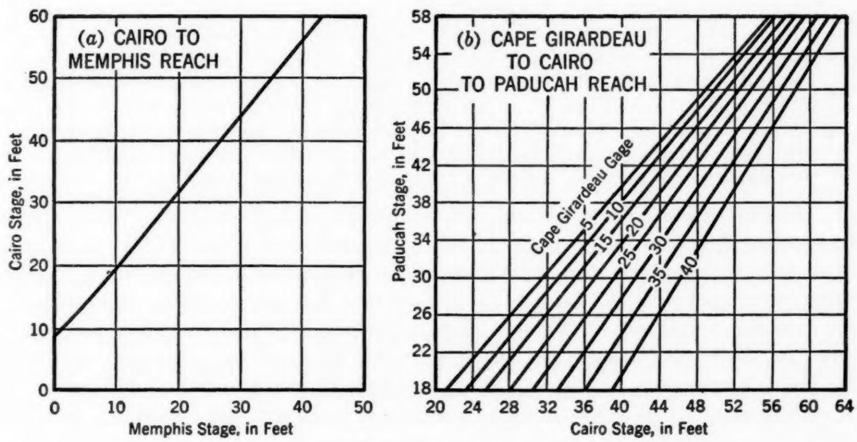

Fig. 1.—Stage Prediction Curves—Mississippi River

Single Line Curves.—The inadequacy of these rules of thumb to yield results of the degree of accuracy required led to the development of stage prediction methods that incorporated the records of previous floods. One of the simplest of these was the construction of single-line stage relation curves, similar to the one for the Cairo to Memphis, Tenn., reach shown in Fig. 1 (*a*). This type of diagram, containing only two factors (the stage at the

upper end of the reach and the corresponding stage at the lower end of the reach) is usually constructed by plotting stages observed from past crests and troughs that occurred under conditions essentially the same as those existing at the period for which the chart is to be used. Similar charts for determining the time required for flows to pass through the reach may be constructed by plotting the upstream stages against the observed time between the corresponding upstream and downstream gages.

The fact that single-line stage relation curves, especially for the higher stages, usually take the form of straight or nearly straight lines led to the custom of expressing the graphical relationship by an equation of the form

$$h_L = a\,h_U + b \qquad (1)$$

in which a and b are constants and h_L and h_U are the corresponding stages at the lower and upper ends of the reach. Equations of this type were used for predicting stages on the Rhine River,[3] Germany, as early as 1903, and it was claimed that with some exceptions the variation between floods predicted on the Rhine and floods that actually occurred did not exceed 20 cm. Curtis McD. Townsend, a former president of the Mississippi River Commission, states[4]

> "Since the Rhine rises in the Alps, and since its discharge is regulated by Lake Constance, it frequently has a flood when its lower tributaries are discharging little water. Hence the primary wave is more readily determined than in the rivers of the United States, whose tributaries, flowing at all stages with great irregularity, interfere with the primary wave flowing down the main stream. On the long rivers of the United States this method would not give as satisfactory results. Gage stations on the Rhine are less than 20 kilometers apart on the average; while on the Ohio River and on the Mississippi River they are frequently more than 100 miles apart, and it is necessary to make predictions over river distances of from 300 to 1500 miles. An error of 20 centimeters between stations on the Rhine may readily correspond to an error of from 10 to 20 feet on the Ohio between Cincinnati and Cairo, since the principal tributaries of the Rhine empty into the main stream within a distance of 150 kilometers."

Multiple Line Charts.—Since the single-line diagram is applicable only to reaches of the main stream in which, or immediately below which, no important tributary enters, the development of multiple-line charts, such as the one presented by E. W. Lane,[5] M. ASCE, was necessary. With these charts, for instance, the stages at Paducah, Ky., on the Ohio River and Cape Girardeau, Mo., on the upper Mississippi River are used to determine the stage at Cairo for the following day. Fig. 1(b) is an example of this type of chart.

The entrance of more than one tributary into a reach of the main river further complicates the use of stage relations for stage forecasting. The entrance of the White River and the Arkansas River into the Mississippi River just above the Arkansas City (Ark.) gaging station provides a good example of the effect of tributary flow.

[3] "Etude Hydrologique du Rhin Allemand et du Main, les Crues, et leur Prévision," par M. Ed. Maillet, Annales des Ponts et Chaussées, Mémoires et Documents, 1903, p. 200.

[4] "The Hydraulic Principles Governing River and Harbor Construction," by Curtis McD. Townsend, The Macmillan Co., New York, N. Y., 1922, p. 42.

[5] "Predicting Stages for the Lower Mississippi," by E. W. Lane, *Civil Engineering*, Vol. 7, February, 1937, p. 122.

In 1927 the combined crest discharges of the White River and Arkansas River amounted to approximately 40% of the total Mississippi River flow at Arkansas City. Unless the effect of these tributaries on main river stages is considered, reliable forecasts for Arkansas City and the stations downstream are impossible. In 1944 Max A. Kohler, Assoc. M. ASCE, developed a forecasting procedure[6] that requires the development of a chart for determining the normal relationship between gages on the main river and of auxiliary charts (one for each tributary) that are used to determine the corrections to be applied to the predicted normal stages. Charts of the type shown in Fig. 2 were developed by Mr. Kohler for use in predicting stages at Arkansas City.

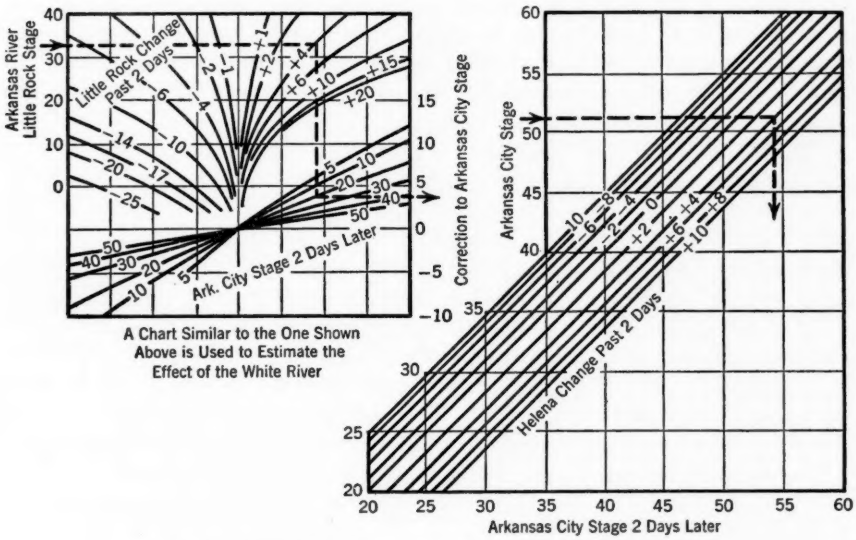

Fig. 2.—Routing Curves—Helena to Arkansas City Reach

Methods of this type permit the predictions of future stages without the use of discharge observations or stage discharge curves. If discharge data are available, the method can be simplified by use of a single multiple-line chart which evaluates the effects of tributary flow on main river stages. Fig. 3 used for predicting crest stages at Red River Landing, La., is an example of this type of chart. For day-by-day stage forecasting the effects of changes in tributary flow on main river stages, either positive or negative, can be considered by using charts of the type shown in Fig. 4.

Forecasting Techniques

Limitations of Forecasting.—Gaging stations on tributaries are usually located a considerable distance above the mouth to avoid the influence of backwater from the main river. Successful stage forecasting requires consid-

[6] "A Forecasting Technique for Routing and Combining Flow in Terms of Stage," by Max A. Kohler, *Transactions*, American Geophysical Union, Vol. 25, 1944, p. 1030.

eration of the time necessary for fluctuations in stage or discharge at the tributary station to reach the main river.

Stage relation diagrams give the average relation between gages. The variation in the rate of storage in the overbank areas and in the channel itself, as the water surface rises or falls, is not taken into account. For that reason stage relation diagrams are more accurate in reaches where the capacity for storage is relatively small. The Mississippi River below Red River Landing is closely confined by levees, and storage is a minor factor. Stage relation diagrams give very good results in this reach. The reach between Helena, Ark., and Red River Landing contains several large areas which are subject to overflow by backwater from the river. Storage is an important factor in this reach, and the use of stage relation diagrams does not give reliable results.

Application of Techniques to the Mississippi River.—Forecasting techniques that use selected headwater stations as indexes for predicting stages in the main valley have been evolved. Three days in advance M. Belgrand was

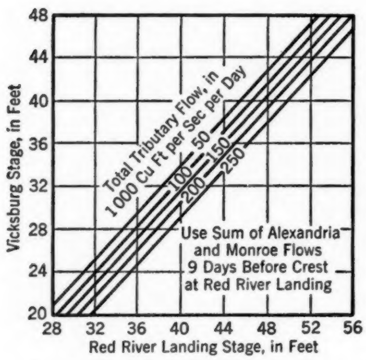

FIG. 3.—CHART FOR DETERMINING STAGE RELATIONS MISSISSIPPI RIVER—VICKSBURG TO RED RIVER LANDING REACH

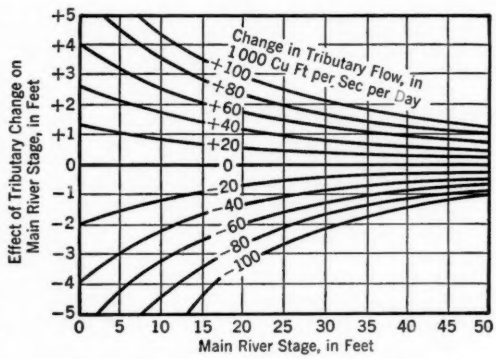

FIG. 4.—TYPICAL CHART FOR DETERMINING EFFECT OF FLUCTUATIONS IN TRIBUTARY FLOW

able to predict flood heights at Paris, France, within 40 cm by using this method.[3] Other forecasters have frequently used tabulations that listed the crest rise in feet per inch of rainfall for large storms on headwater basins. Because of the tremendous drainage area of the Mississippi River, neither the index station method nor the unit crest method is applicable.

The method used by the Stage Prediction Section of the Mississippi River Commission for forecasting flood stages on the lower Mississippi River is a modification of the graphical method of flood routing developed by Louis G. Puls,[7] Assoc. M. ASCE. During flood periods daily discharge observations are made at the principal gaging stations. The results of these observations are used to develop stage-discharge relation curves that are applicable to the individual flood only. For forecasting purposes these stage-discharge curves are extended as far beyond the limits of the observed data as necessary, the extrapolation being shaped by comparison with data from previous floods.

[7] "Flood Regulation of the Tennessee River," by Louis G. Puls, *House Document No. 185*, 70th Congress, 1st Session, Appendix B, Part II, U. S. Govt. Printing Office, Washington, D. C., 1928.

These curves are then used to determine the daily inflows and outflows at the upper and lower ends of each reach. Similar curves are used to determine the daily contributions from the tributaries. Runoff from rainfall occuring over the ungaged areas below the tributary gaging stations is computed by the use of unit graphs. The observed inflows (main river and tributaries) are then combined with the runoff computed from local rainfalls and reverse routed, using the observed reach outflows, to develop stage-storage curves for the various reaches. These storage curves are then extended beyond the limit of the available data by comparison with similar storage curves for previous floods.

During the progress of a flood, five-day forecasts of the discharges to be expected at Thebes, Ill., on the upper Mississippi River, at Golconda, Ill., on the Ohio River, and at Smithland, Ky., on the Cumberland River, are made by the Corps of Engineers offices responsible. In addition to these forecasts there is also available a five-day forecast of anticipated releases from Kentucky Dam on the Tennessee River furnished by the Tennessee Valley Authority (TVA). The predicted flows at Thebes, Golconda, Smithland, and Kentucky Dam are then combined with the estimated runoff from the ungaged area between these stations and Cairo to obtain the total daily inflows to the Thebes-Golconda-Cairo Reach. The predicted daily flows are then routed through the reach using the method previously mentioned to obtain the predicted daily stages and discharges at Cairo. These predicted discharges are then combined with the estimated tributary and local inflows between Cairo and Memphis and routed in a similar manner to obtain the predicted daily stages and discharges at Memphis. The same routine is followed in making forecasts for Helena, Arkansas City, Vicksburg, Natchez (Miss.), and Red River Landing.

A portion of a typical flood routing table for the Thebes-Golconda-Cairo Reach is shown in Table 1. The flood routing table is developed in the following manner: Values of reach outflow (Q) and reach storage (S) for stage intervals of 1 ft are obtained from the stage-discharge and stage-storage curves for the reach. The remainder of the table is developed at 1-ft intervals by subtracting one-half the value of Q from the corresponding storage value to obtain the value shown in Col. 4, Table 1, and by adding one half the value of Q to the corresponding value of S to obtain the value shown in Col. 5, table 1. Intermediate values of both base and indication are determined by interpolation between the values computed at the 1-ft intervals.

The routing table thus developed is used as shown in Table 2. For a stage at Cairo of 50.0 ft at the beginning of the first time period, the base value of 2,303,000 cu ft per sec per day is obtained from the routing table (Table 1). The average inflow of 1,332,000 cu ft per sec per day during the first time period added to the base value, results in a total of 3,625,000 cu ft per sec per day. The value in the indication column of the routing table that most nearly agrees with this total is 3,633,000 cu ft per sec per day, corresponding to a stage of 50.4 ft. This is the stage at the end of the first time period and at the beginning of the second time period. The process is repeated for subsequent time periods.

It is axiomatic that the ability to reproduce an observed hydrograph is the principle criterion for evaluating any method for flood routing. Comparisons of the observed hydrographs of the 1944 and 1945 floods at Cairo and Arkansas City with the hydrographs computed by the method described are shown in Fig. 5.

As previously mentioned the reach below Red River Landing is not seriously affected by storage or inflow from tributaries. Consequently single-line stage relation diagrams are used to predict stages in this reach with very close agreement between forecasted and observed stages being obtained. In considering the use of stage-discharge diagrams for forecasting in the lower reaches of the river, it should be noted that errors of as much as 1 ft in forecasts are quite frequent if a diagram representative of average conditions is used. As a means of reducing errors to a minimum, observed stages are plotted daily during the progress of the flood and the resulting relationship extended in accordance with similar curves for previous floods. By using this procedure, the forecasts are based on the relationship existing for the individual flood instead of on the mean relationship determined from previous floods.

TABLE 1.—ROUTING TABLE FOR THE THEBES-GOLCONDA TO CAIRO REACH

Stage (feet)	Flow Characteristics, in Thousands of Cubic Feet per Second per Day			
	Outflow, Q	Storage, S	Base $S - Q/2$	Indication $S + Q/2$
(1)	(2)	(3)	(4)	(5)
50.0	1,242	2,924	2,303	3,545
50.1			2,320	3,567
50.2			2,337	3,589
50.3			2,354	3,611
50.4			2,371	3,633
50.5			2,388	3,655
50.6			2,405	3,677
50.7			2,422	3,699
50.8			2,439	3,721
50.9			2,456	3,743
51.0	1,292	3,119	2,473	3,765
51.1			2,491	3,789
51.2			2,509	3,813
51.3			2,527	3,837
51.4			2,545	3,861
51.5			2,563	3,885
51.6			2,581	3,909
51.7			2,599	3,933
51.8			2,617	3,957
51.9			2,635	3,981
52.0	1,352	3,329	2,653	4,005

TABLE 2.—SAMPLE ROUTING FOR THE THEBES-GOLCONDA TO CAIRO REACH

Period	Average inflow, in thousands of cubic feet per second per day	Base plus average inflow	Routed Cairo stage (feet)
(1)	(2)	(3)	(4)
1			50.0
	1,322	3,625	
2			50.4
	1,355	3,726	
3			50.8
	1,370	3,809	
4			51.2
	1,365	3,874	
5			51.5
	1,352	3,915	
6			51.6
	1,320	3,901	
7			51.6
	1,270	3,851	
8			51.4

During the flood period all pertinent data are carefully analyzed as soon as received. Stage-discharge curves are revised if the latest discharge observations indicate that the curves being used have been extended erroneously. If observed stages show a serious variation from the forecast stages, the reach storage curves and routing tables are revised to reflect more nearly the conditions existing during the flood.

By using the method outlined, sufficiently accurate seven-day forecasts for flood stages at Cairo can be made. Stages in the lower reaches of the river have been forecast within reasonable limits for periods of three weeks.

Throughout the critical season very close cooperation is maintained with the TVA, the offices of the United States Weather Bureau throughout the Mississippi River Basin, and the various districts and divisions of the Corps of Engineers, all of which furnish data essential to the success of the fore-

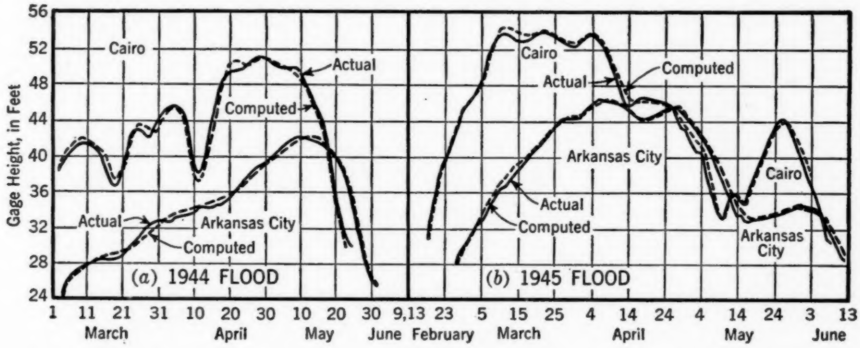

FIG. 5.—ACTUAL AND COMPUTED STAGES OF THE MISSISSIPPI RIVER AT CAIRO AND ARKANSAS CITY

casting procedure. The accuracy obtained by the procedure used is not perfect, but the results are consistently better than those obtained by using any of the other methods described or by using any of the many other forecasting procedures that have been investigated throughout the years. Needless to say continuing investigation and testing of techniques is going on to give greater accuracy and reduce the time and effort required to make sufficiently accurate forecasts.

CONCLUSIONS

Extensive study of the problem of flood-stage forecasting for the lower Mississippi River has led to the following conclusions:

1. Reliable forecasts for the lower Mississippi River cannot be made by using any rigid formula or procedure;
2. Procedures which do not evaluate the effects of current channel conditions, tributary or diversion flows, storage, and precipitation will not give reliable forecasts;
3. Procedures dependent on the use of volumetric principles will give better results than those which are based entirely on stage heights; and
4. Stages on the lower Mississippi River can be forecast with sufficient accuracy to warrant the use of these forecasts as the basis for planning and executing flood-fighting activities.